Effect of damage on performance of composite structures – applications to static and fatigue strength predictions

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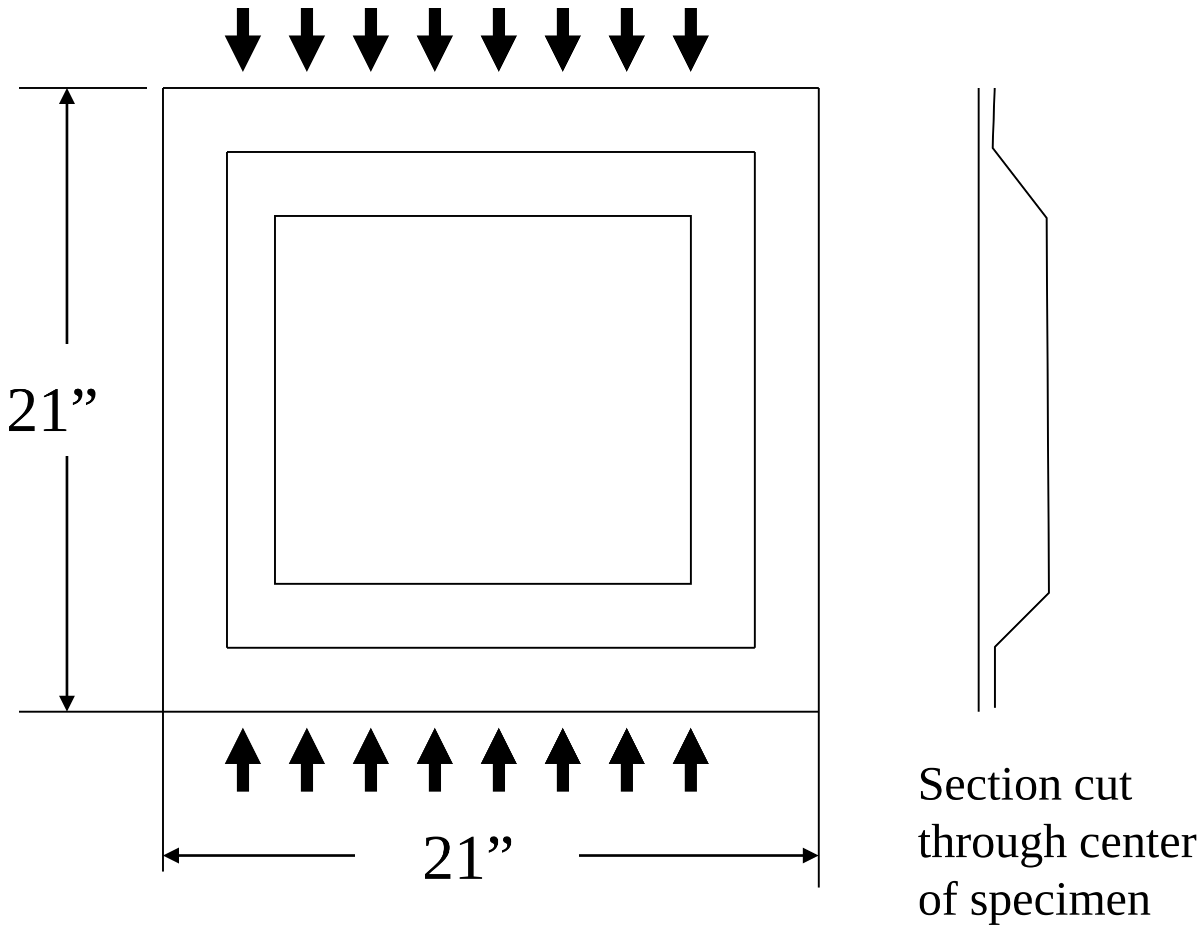
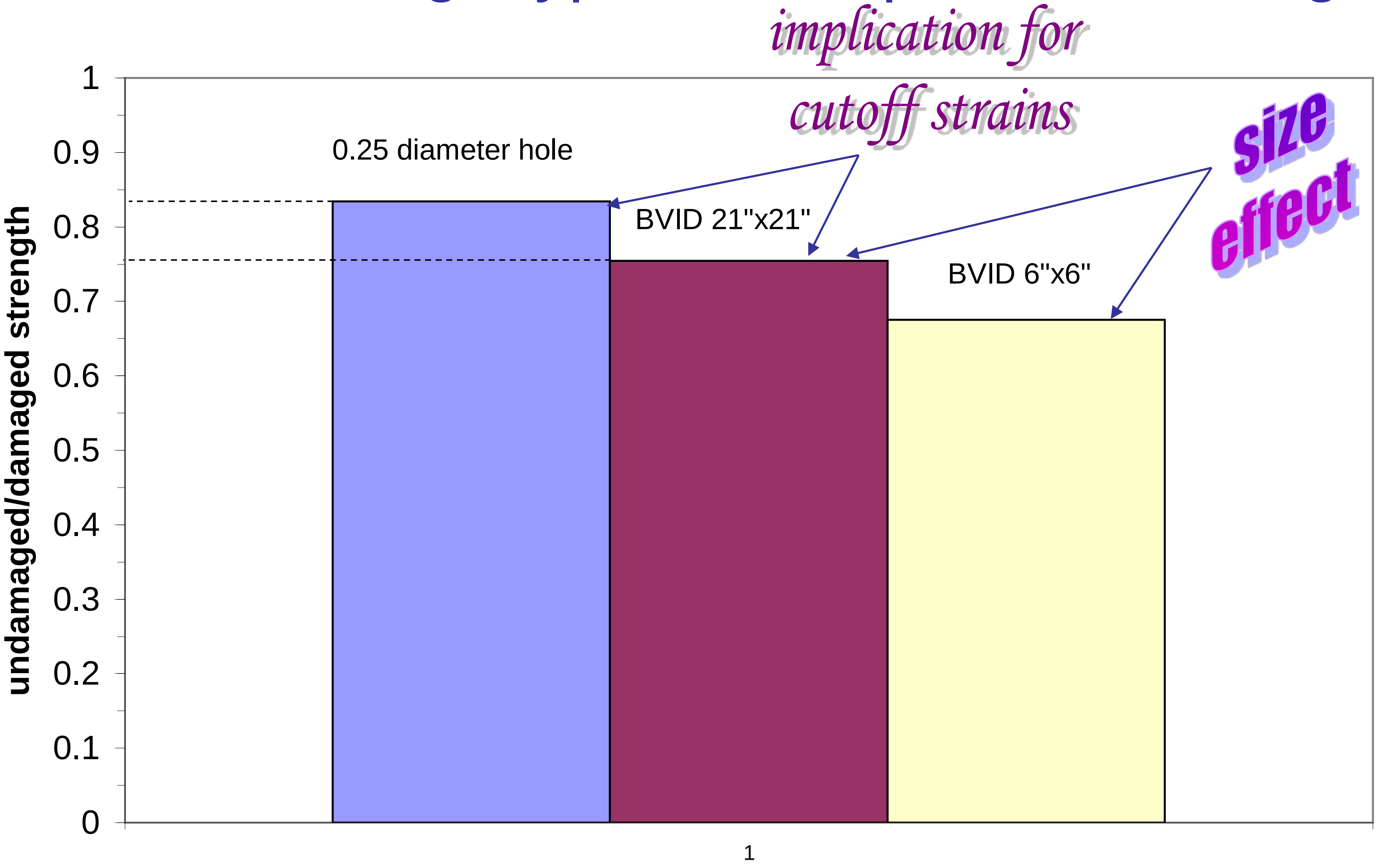
Outline

- static
  - open hole
  - BVID
- fatigue
  - constant amplitude
  - B-Basis curve
  - “Goodman diagram”
  - truncation level determination

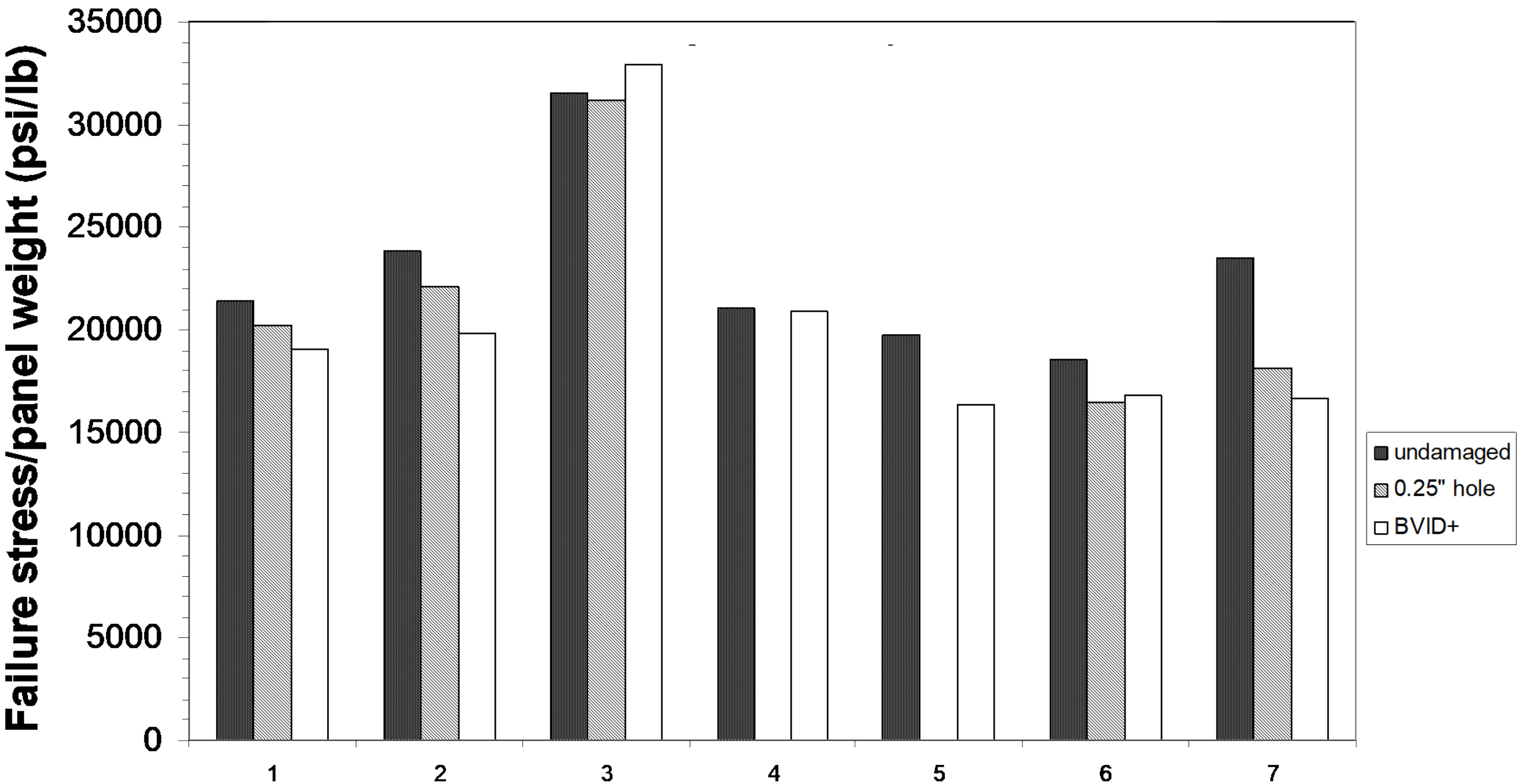
Sandwich with rampdown



Effect of damage type on compression strength

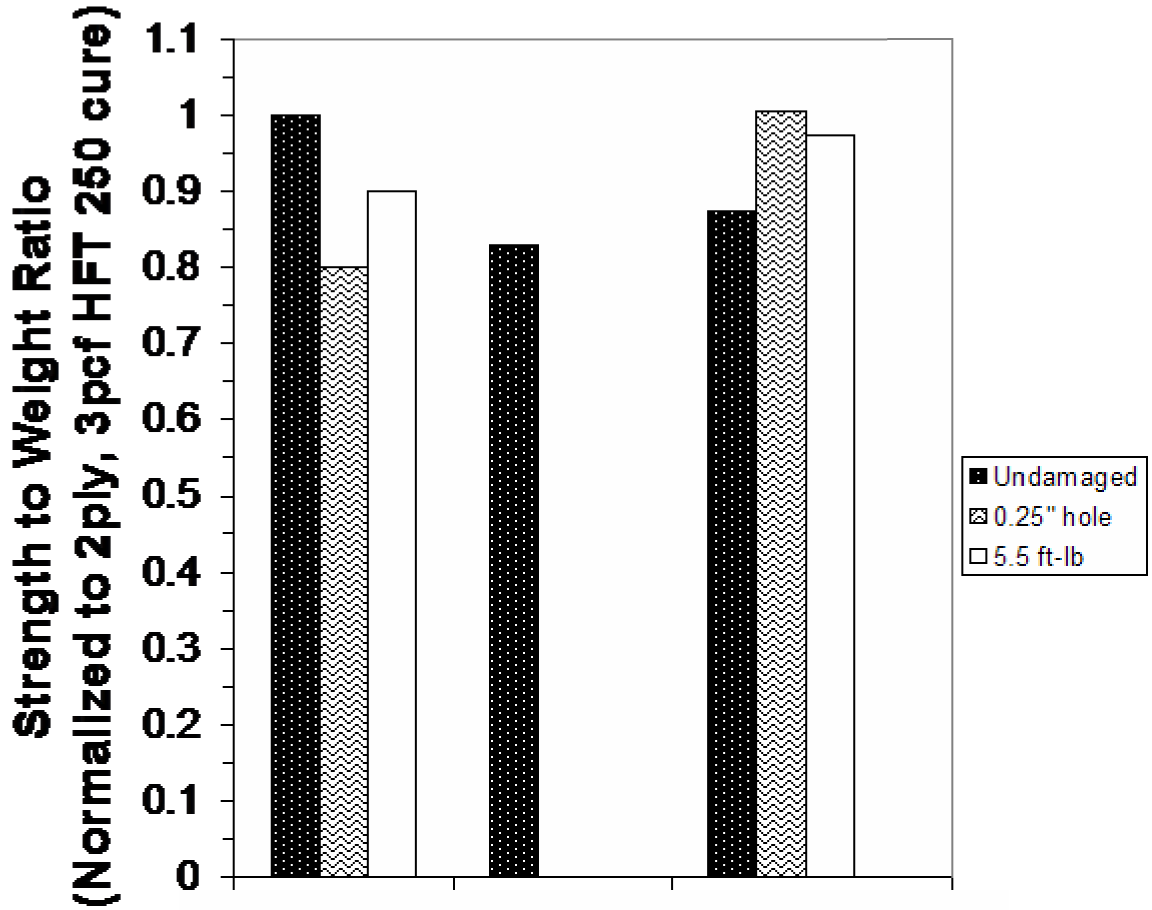


Strength/Weight ratio for various materials and layups (sandwich under compression)



0.25" hole <=> BVID

Strength/Weight ratio for different materials and layup (sandwich under shear)



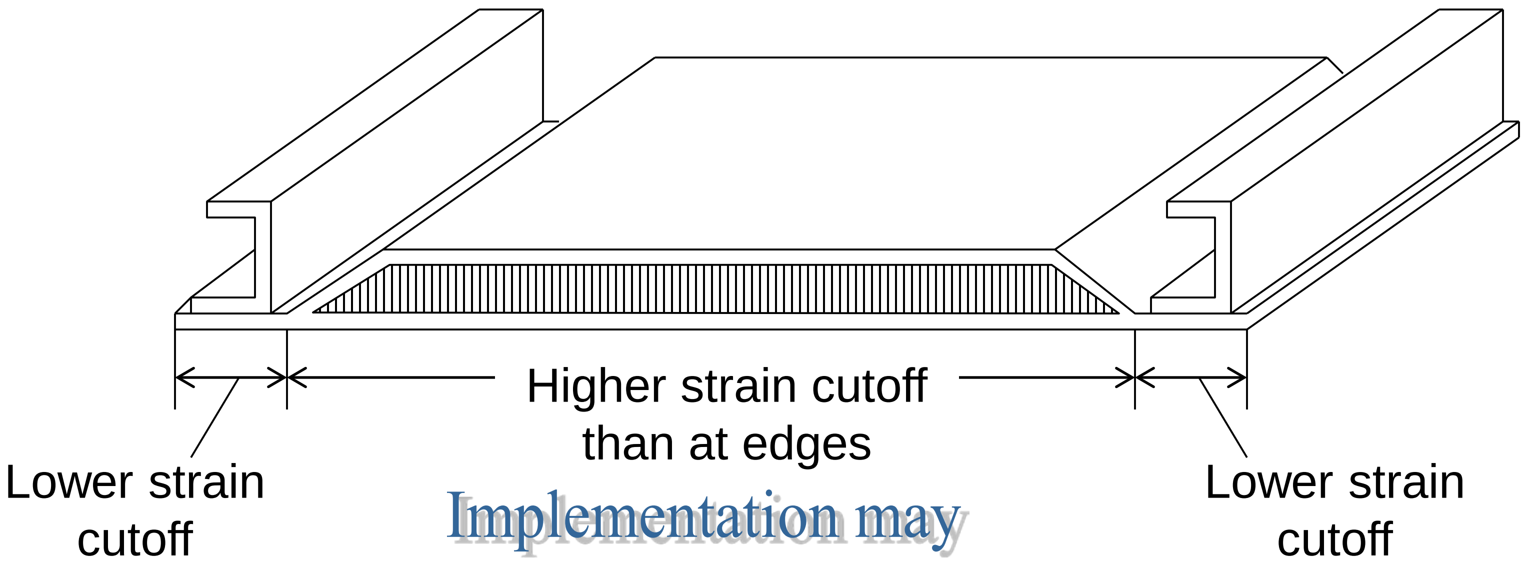
0.25" hole <=> BVID

BVID versus 0.25” hole (sandwich compression or shear)

- Statistically indistinguishable
- Can use 0.25” hole as a simpler test
- Can use hole analysis instead of more complicated impact damage analysis
- Subject to spot checking by tests (may be material dependent)

Cutoff strains

- Small coupon data are conservative
- Different cutoff strain values depending on application

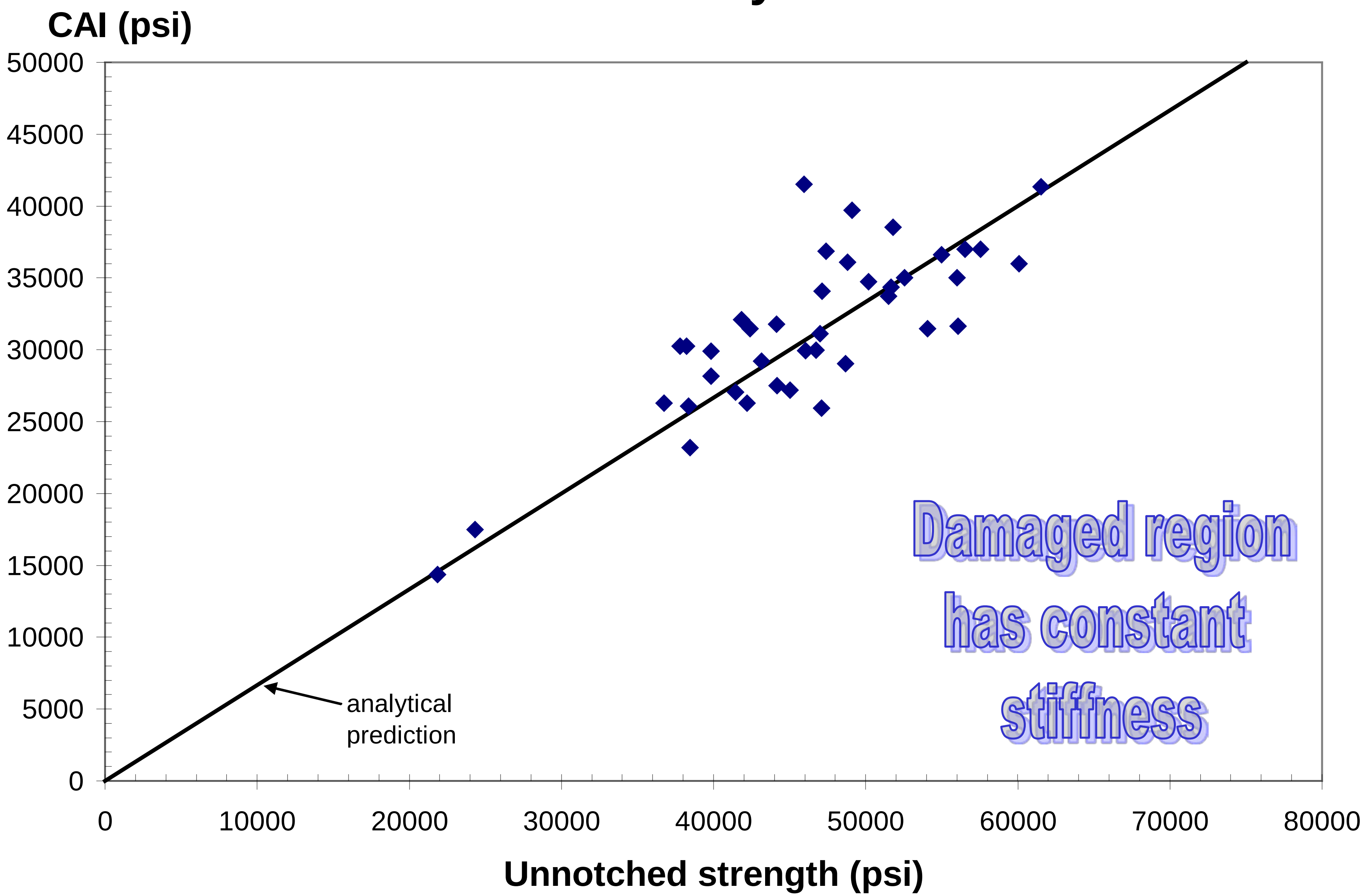


Implementation may
require tailoring!

Modeling impact damage

- Area of reduced stiffness (modulus retention ratio concept)
- Lekhnitskii-based stress analysis for laminate with inclusion – constant stiffness in the damaged region
- Linear variation of stiffness in the damaged region – limited test input required
- ND tests to measure in-plane stiffness of damaged region very worthwhile

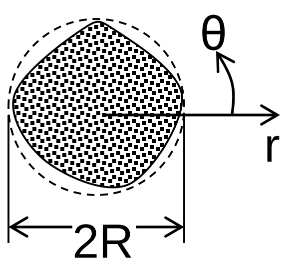
Sandwich CAI – Analysis versus test



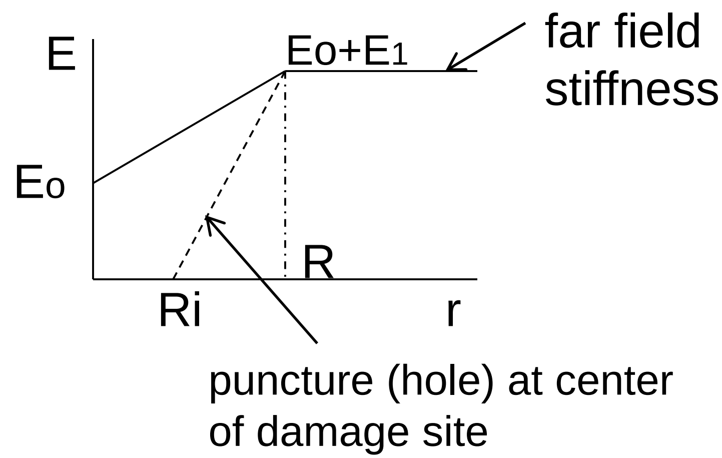
Improved CAI analysis

The approach [1] treats the site with impact damage as an inclusion of different stiffness.
The variation of the stiffness inside the damaged region as a function of the radial distance r (no dependence on θ),

$$E = E_o + E_1 \frac{r}{R}$$



damage site



- calculate average stiffness in damage region
- divide by far-field stiffness (modulus retention ratio)
- compute SCF:

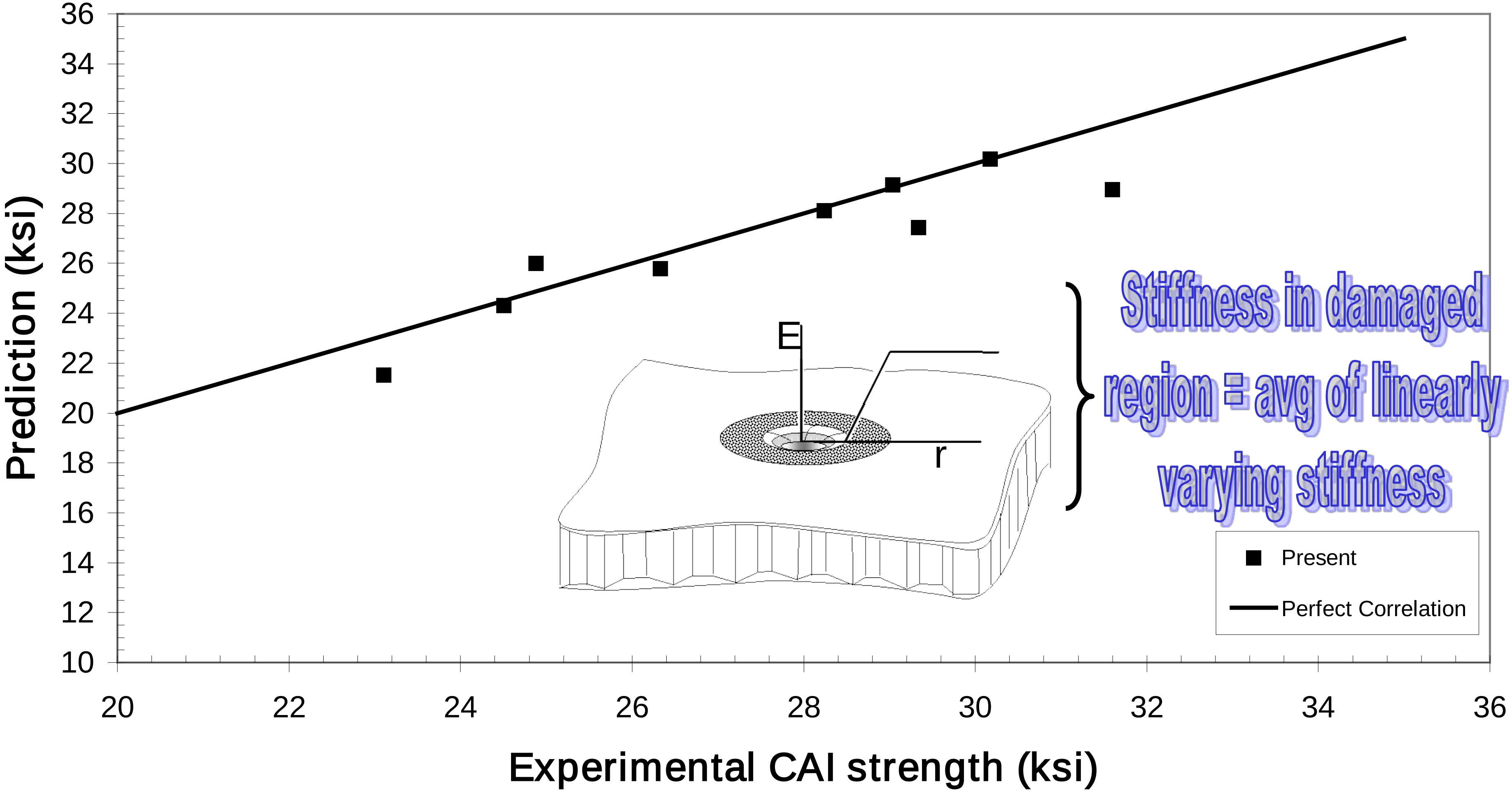
$$SCF = 1-(1-\lambda)\frac{1+\left(\lambda+(1-\lambda)\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}\right)\sqrt{2\left(\sqrt{\dfrac{E_{11}}{E_{22}}}-\nu_{12}\right)+\dfrac{E_{11}}{G_{12}}}+\left(\dfrac{E_{11}}{G_{12}}-\nu_{12}\right)\sqrt{\dfrac{E_{22}}{E_{11}}}}{1+\lambda\left[\lambda+\left(1+\sqrt{\dfrac{E_{22}}{E_{11}}}\right)\sqrt{2\left(\sqrt{\dfrac{E_{11}}{E_{22}}}-\nu_{12}\right)+\dfrac{E_{11}}{G_{12}}}\right]+\left(\dfrac{E_{11}}{G_{12}}-2\lambda\nu_{12}\right)\sqrt{\dfrac{E_{22}}{E_{11}}}-(1-\lambda)^{2}\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}}$$

- calculate CAI strength:

$$\sigma_{CAI} = \frac{\sigma_u}{SCF}$$

Ideally, should create a model that predicts Eo, E1 using NDI data. If not available, constants Eo and E1 can be back-calculated from one specimen and applied to other energy levels. R is measured from one specimen; Ri, if non-zero, assuming linear variation of Eo/(Eo+E1) and the same test specimen

CAI predictions versus test – improved model



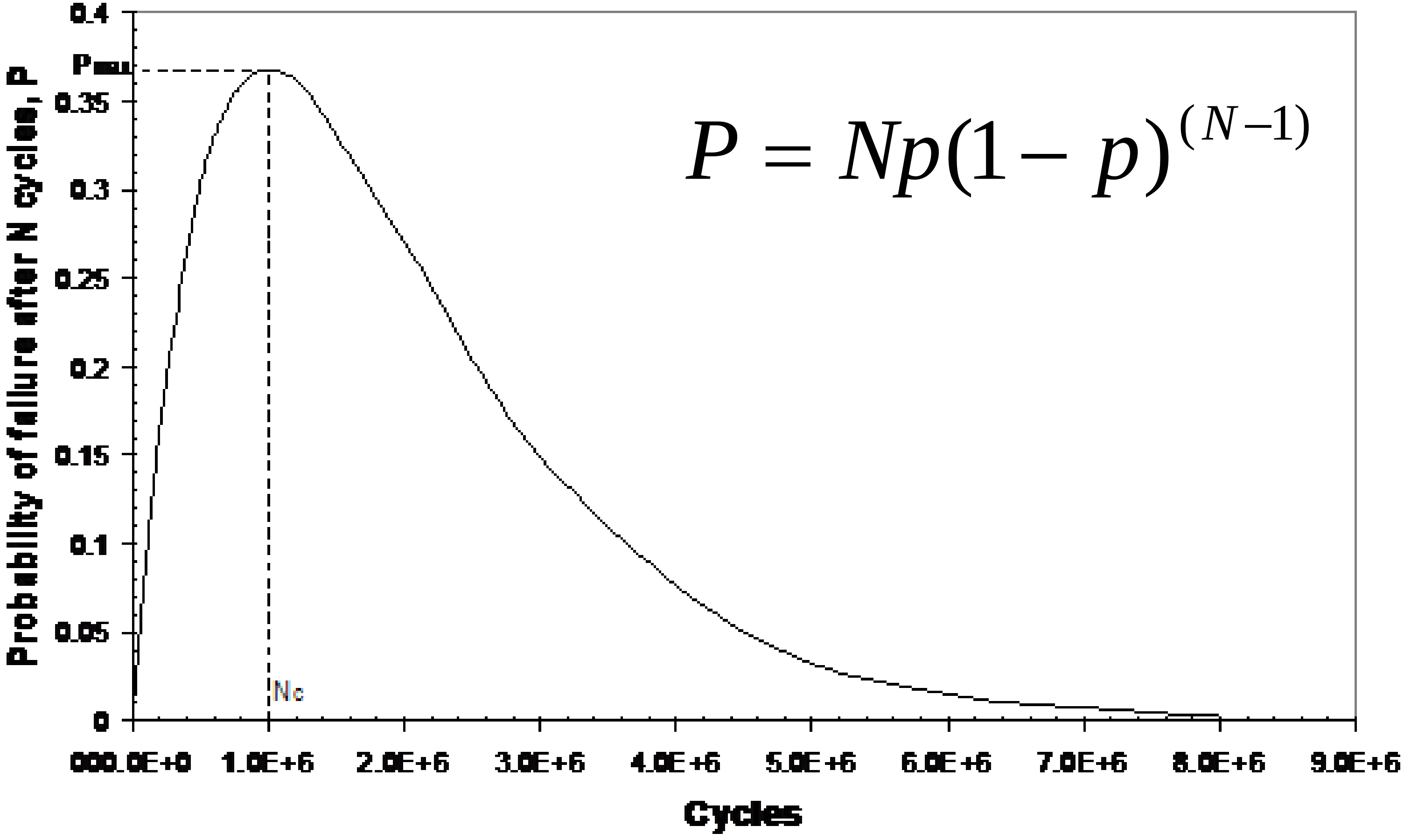
Fatigue analysis (sandwich or monolithic structure)

- Probability of failure p during each cycle
- Probability of failure P after n cycles
- Maximizing P as a function of cycles gives a prediction for the cycles to failure
- p ? In simplest approach assume p=const
- Obtain p from static test data (statistical distribution for static strength gives p)

Fatigue analysis

- R ratio dependence
- Statistical distribution dependence (normal versus 2-parameter Weibull)
- Sensitivity to statistical parameters (scatter)

Fatigue analysis based on the probability of failure



$$P = Np(1-p)^{(N-1)}$$

Cycles to failure

$$N_c = -\frac{1}{\ln(1-p)}$$

$$p = 1 - 0.5\left[1 - \left[1 + \left(A + BZ_p\right)^C\right]^D + \left[1 + \left(A - BZ_p\right)^C\right]^D\right]$$

$$Z_p = \frac{\left|\sigma_{\max} - X_m\right|}{s}$$

$A = 0.644693$

$B = 0.161984$

$C = 4.874$

$D = -6.158$

Normal distribution

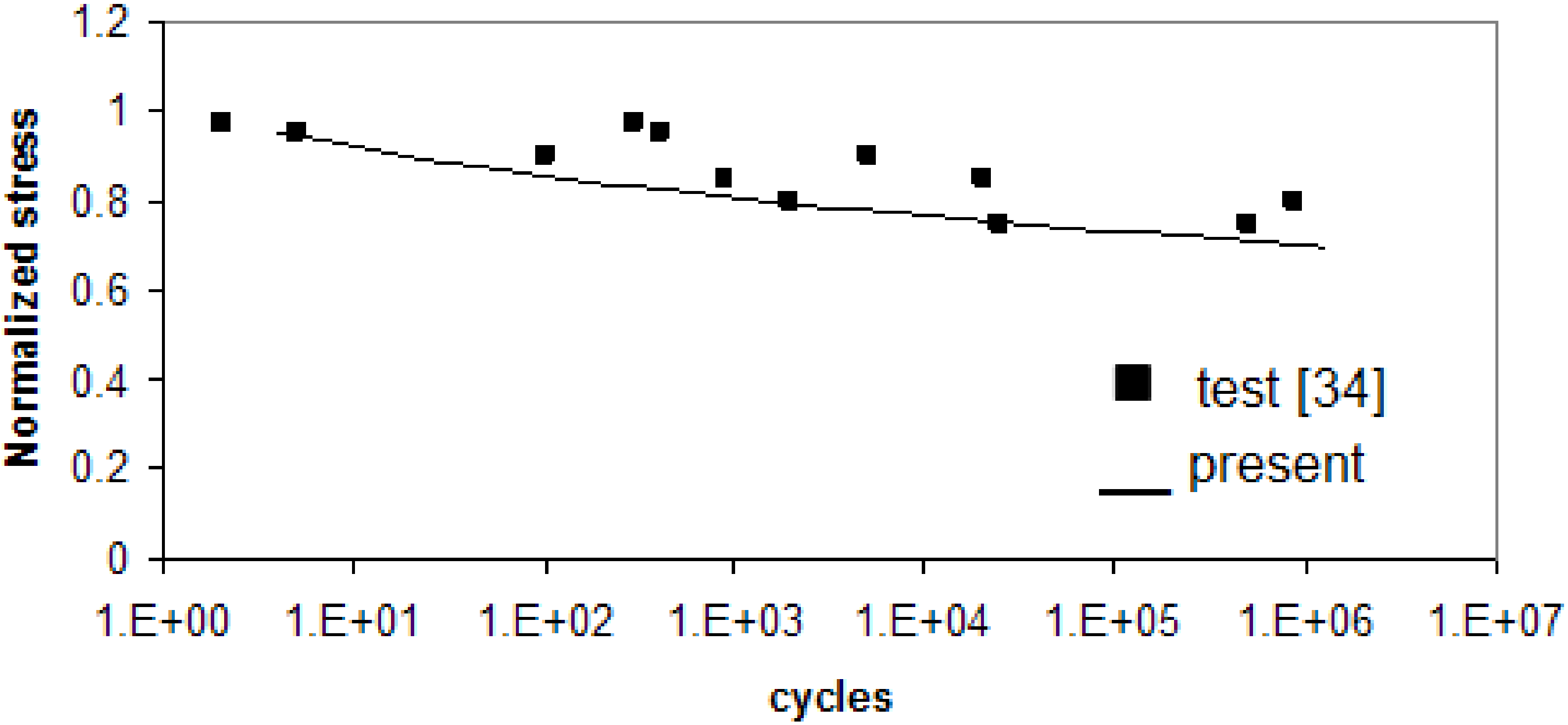
$$\sigma_{\max} = \beta\left(\frac{1}{N_f}\right)^{\left(\frac{1}{\alpha}\right)}$$

2 par Weibull with

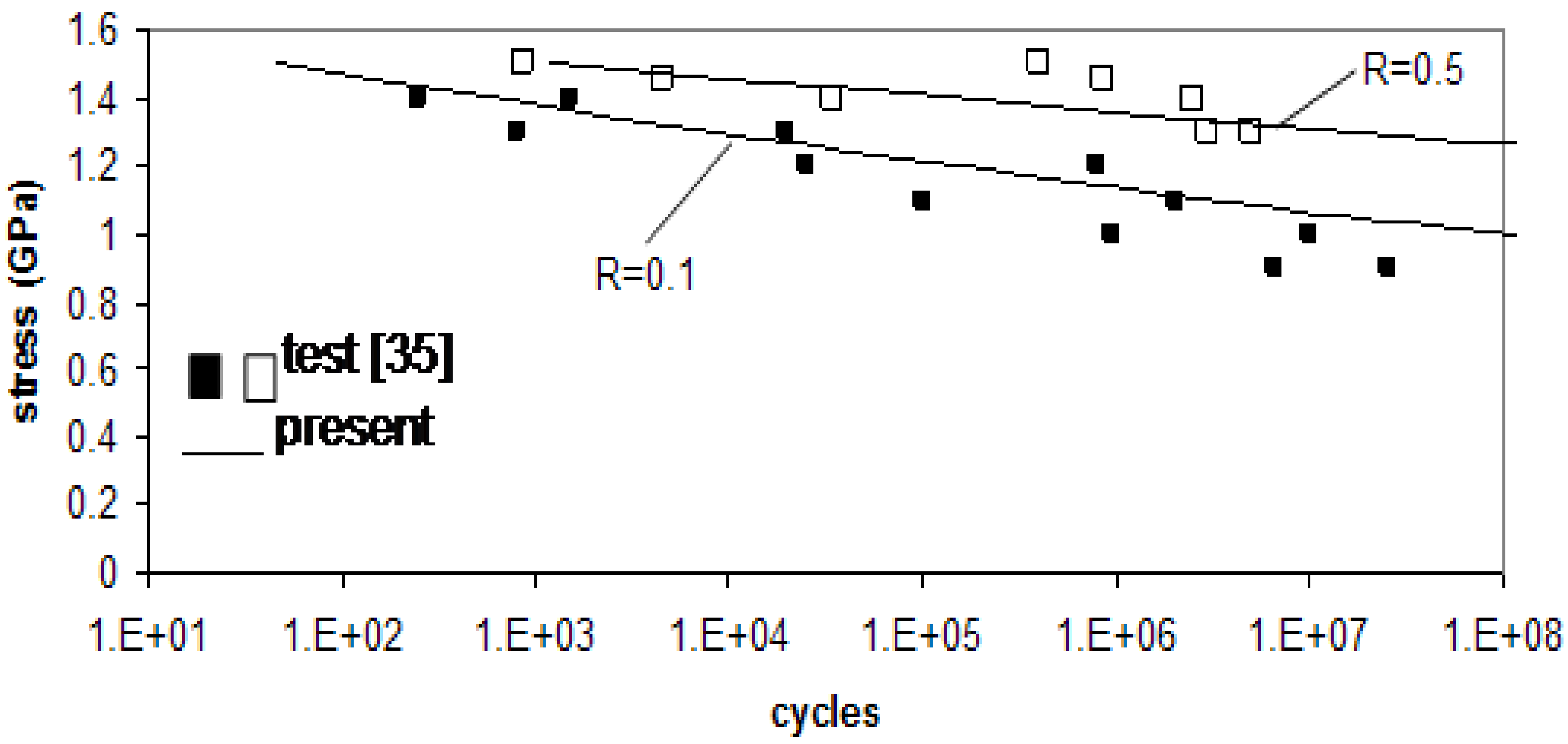
α shape parameter and

β scale parameter

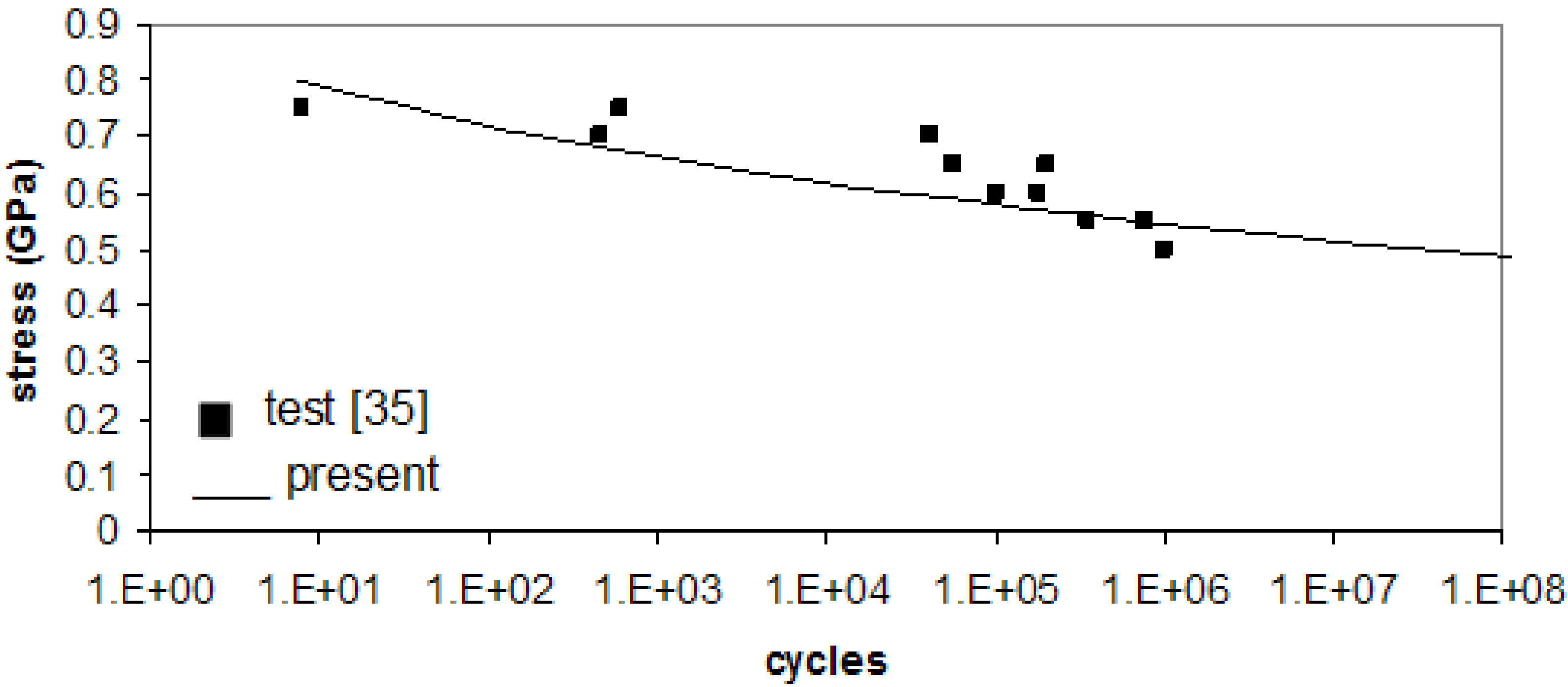
Unidirectional AS4/3501-6 with R=0.



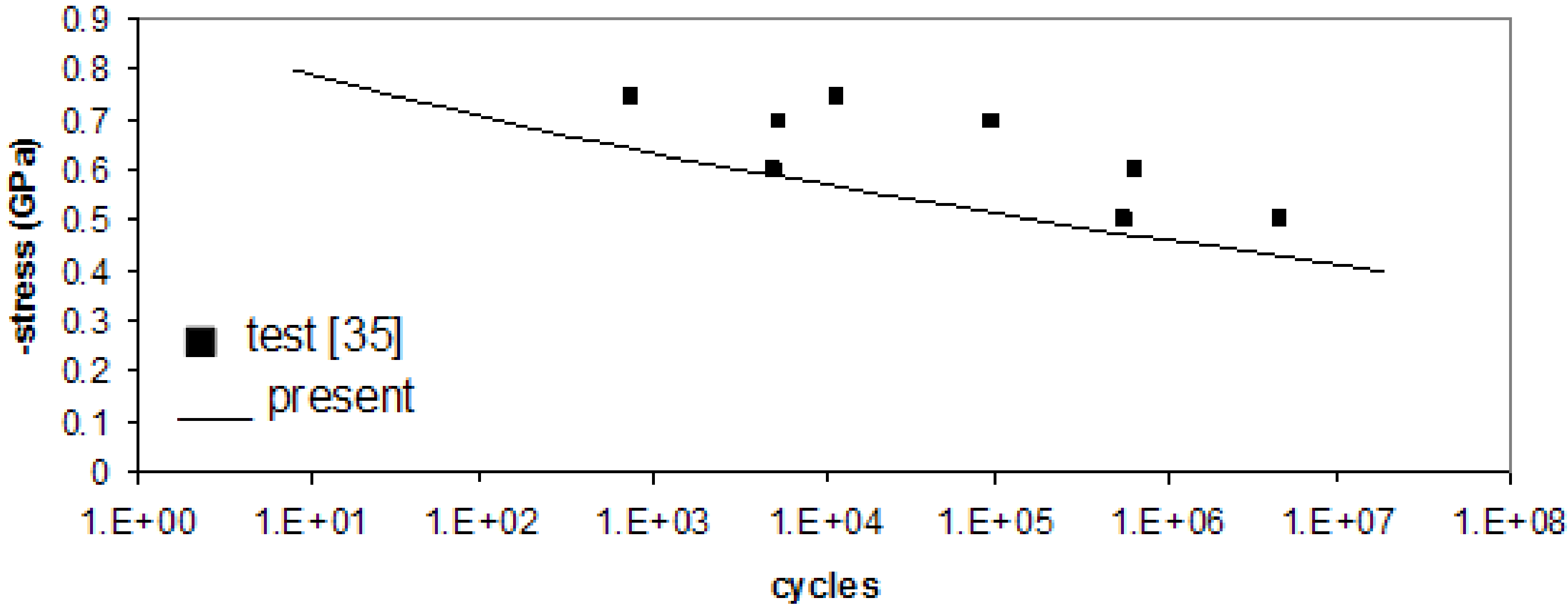
Tension-tension fatigue for [(±45/02)2]s T800/5245



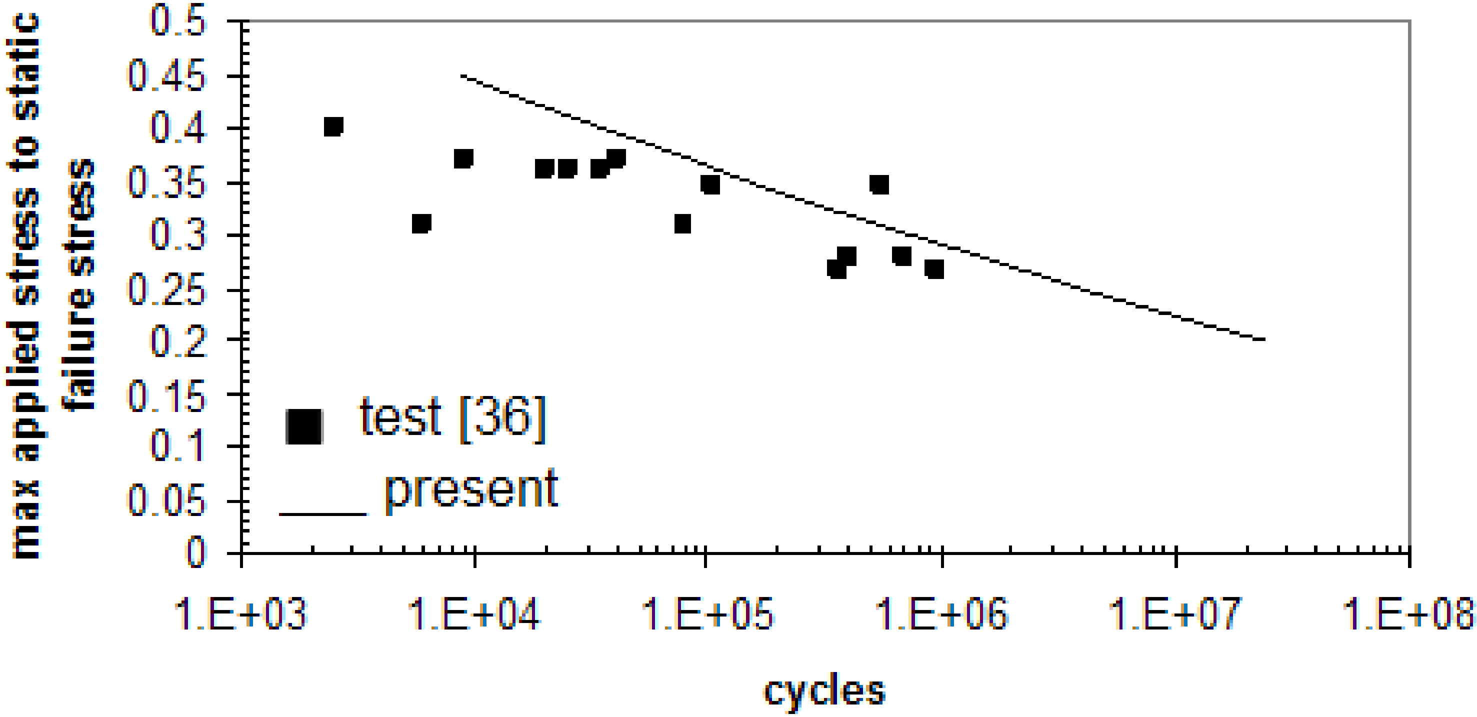
Tension-compression fatigue (R=-1) for [(±45/02)2]s T800/5245



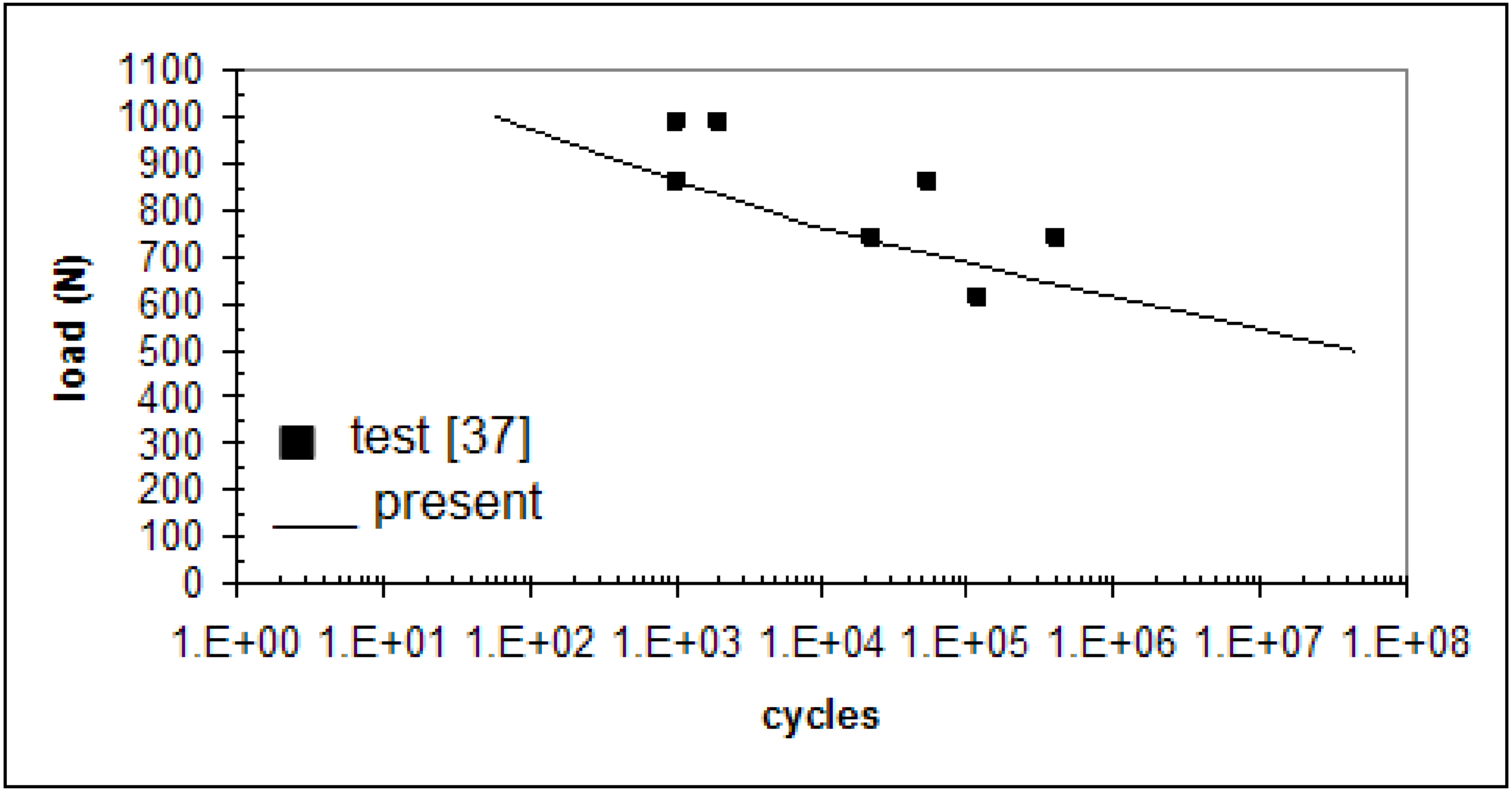
Compresion-compression fatigue **(R=10)** for [(±45/02)2]s T800/5245



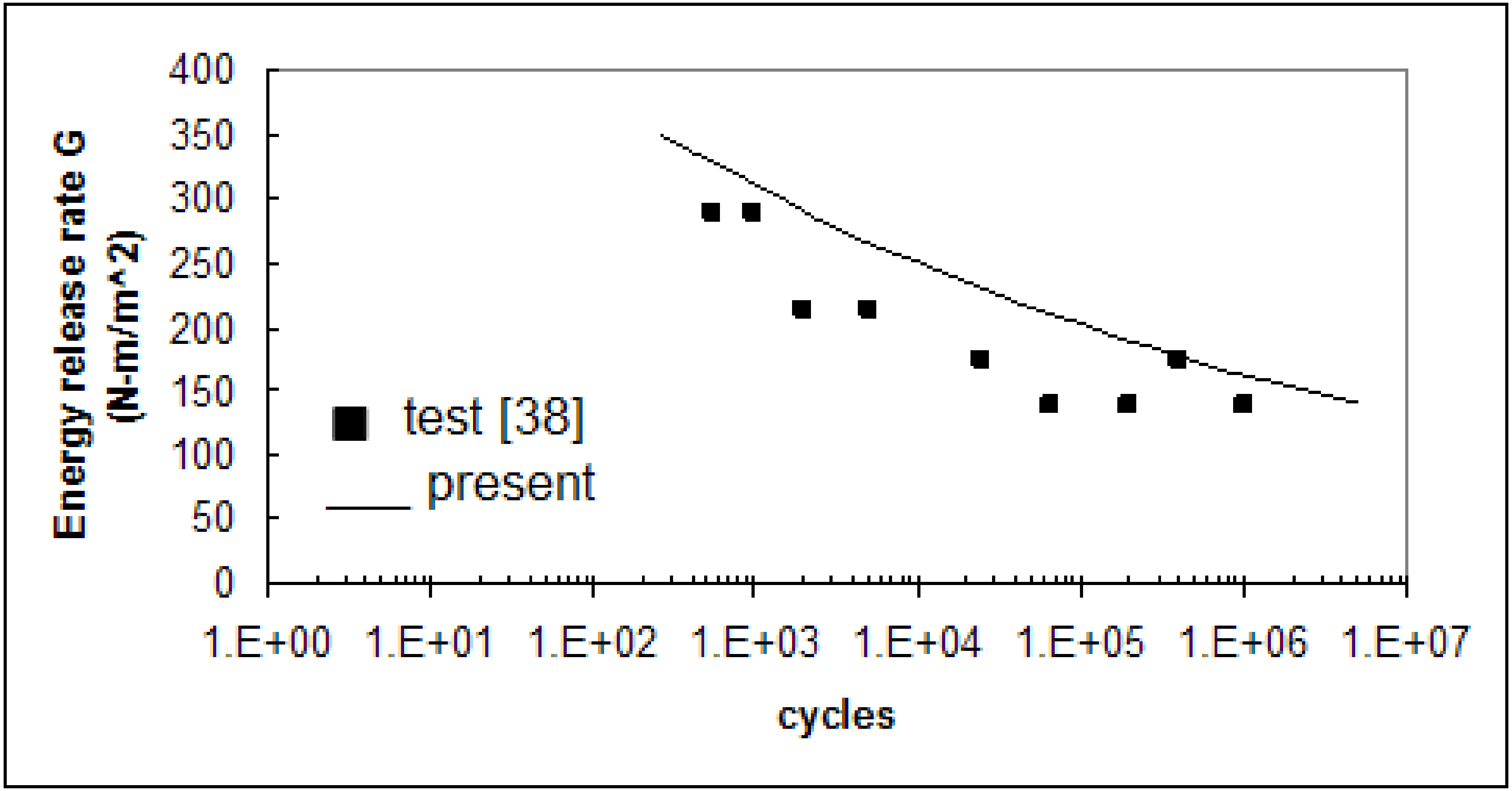
Tension-Torsion case (tension=torsion and R=0) for woven glass fabric



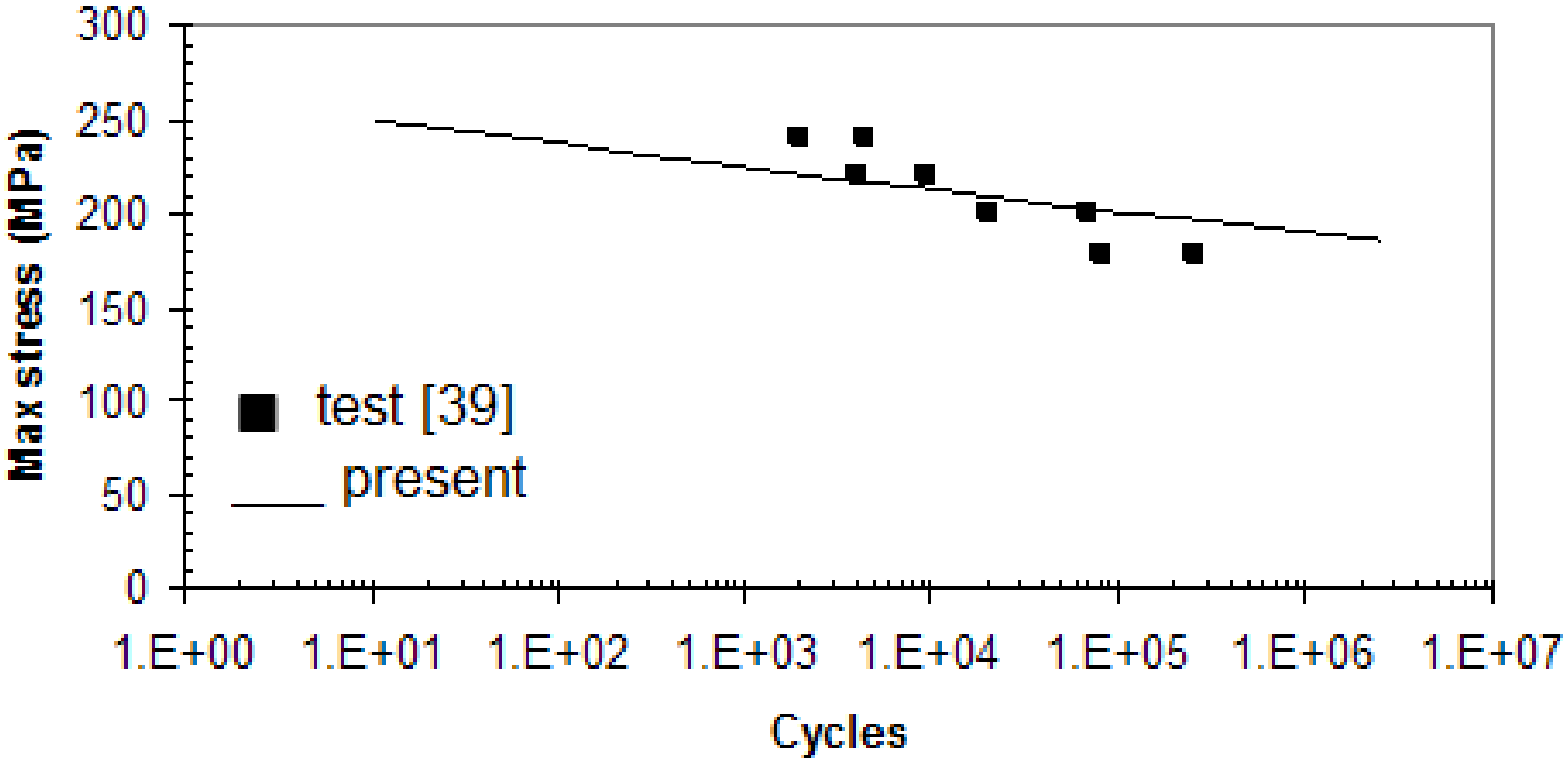
Onset of delamination load for skin/stiffener configuration (R=0.1, IM6/3501-6 material)



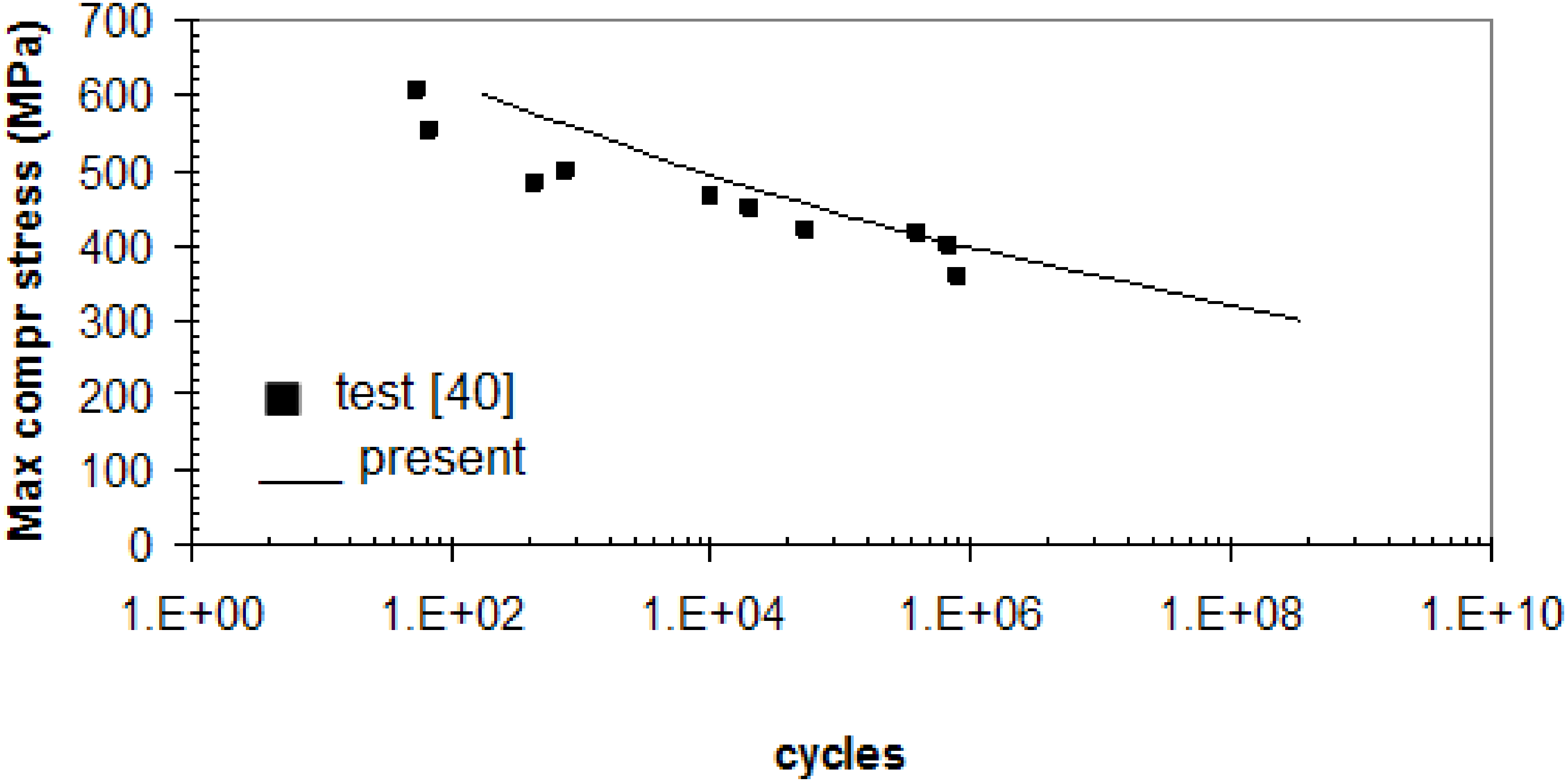
. Onset of edge delamination for $[35_2/-35_2/0_2/90_2]_s$ AS4/PEEK (R=0.1)



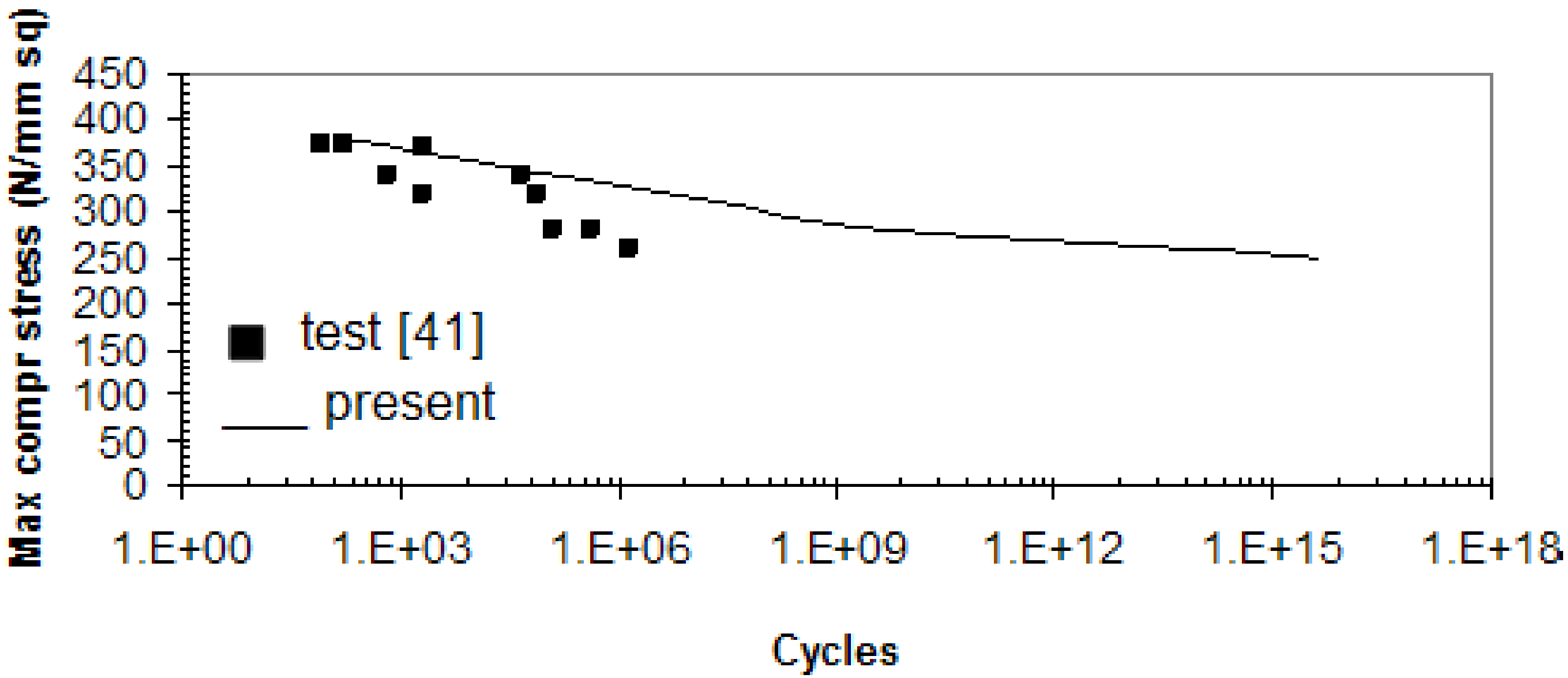
Onset of delamination for quasi-isotropic glass/epoxy (R=0.1)



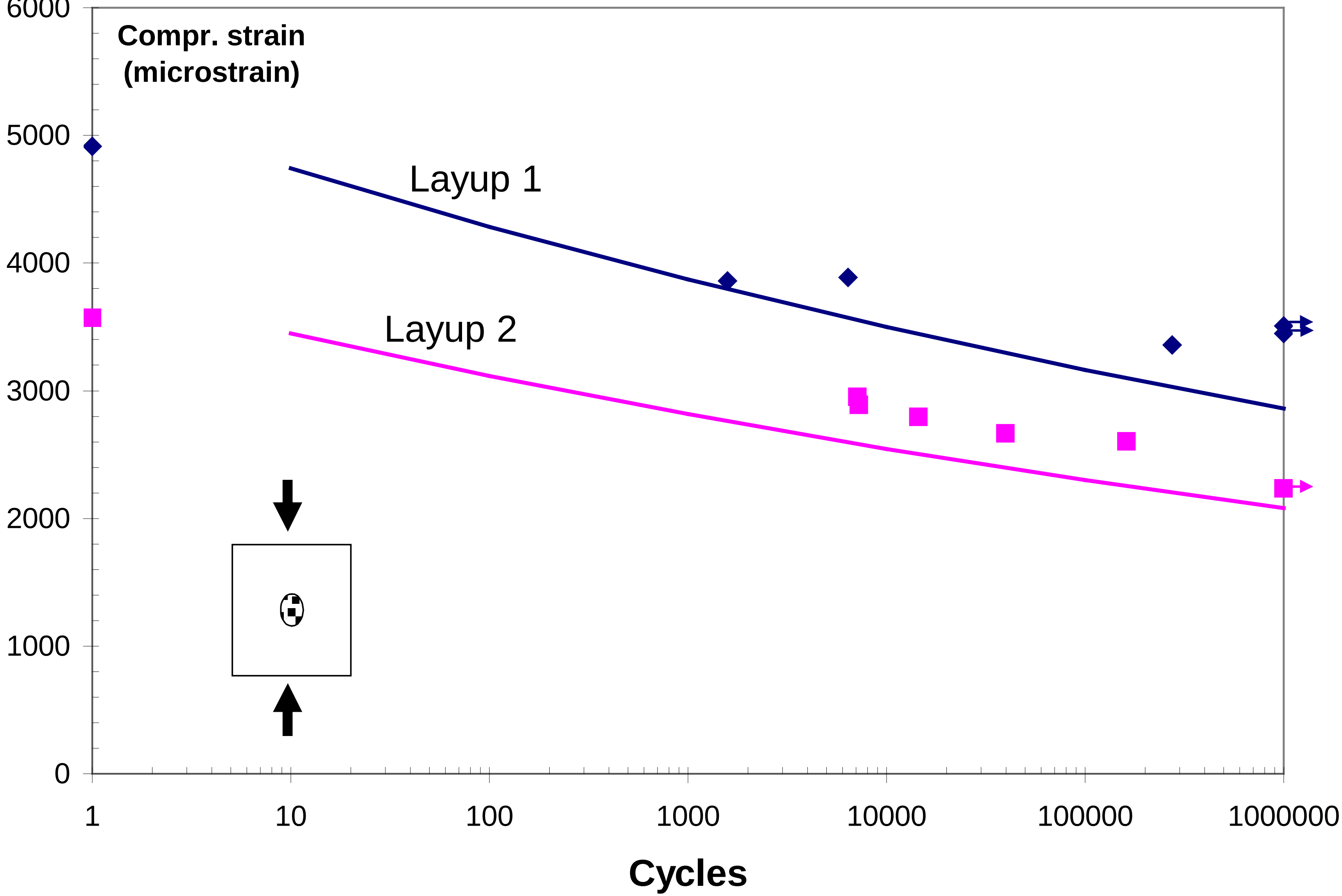
Tension-compression fatigue (R=-1) of [02/±45/02/±45/90]s BMI laminate



Tension-Compression (R=-1.66) failure of T300/914 bolted joints



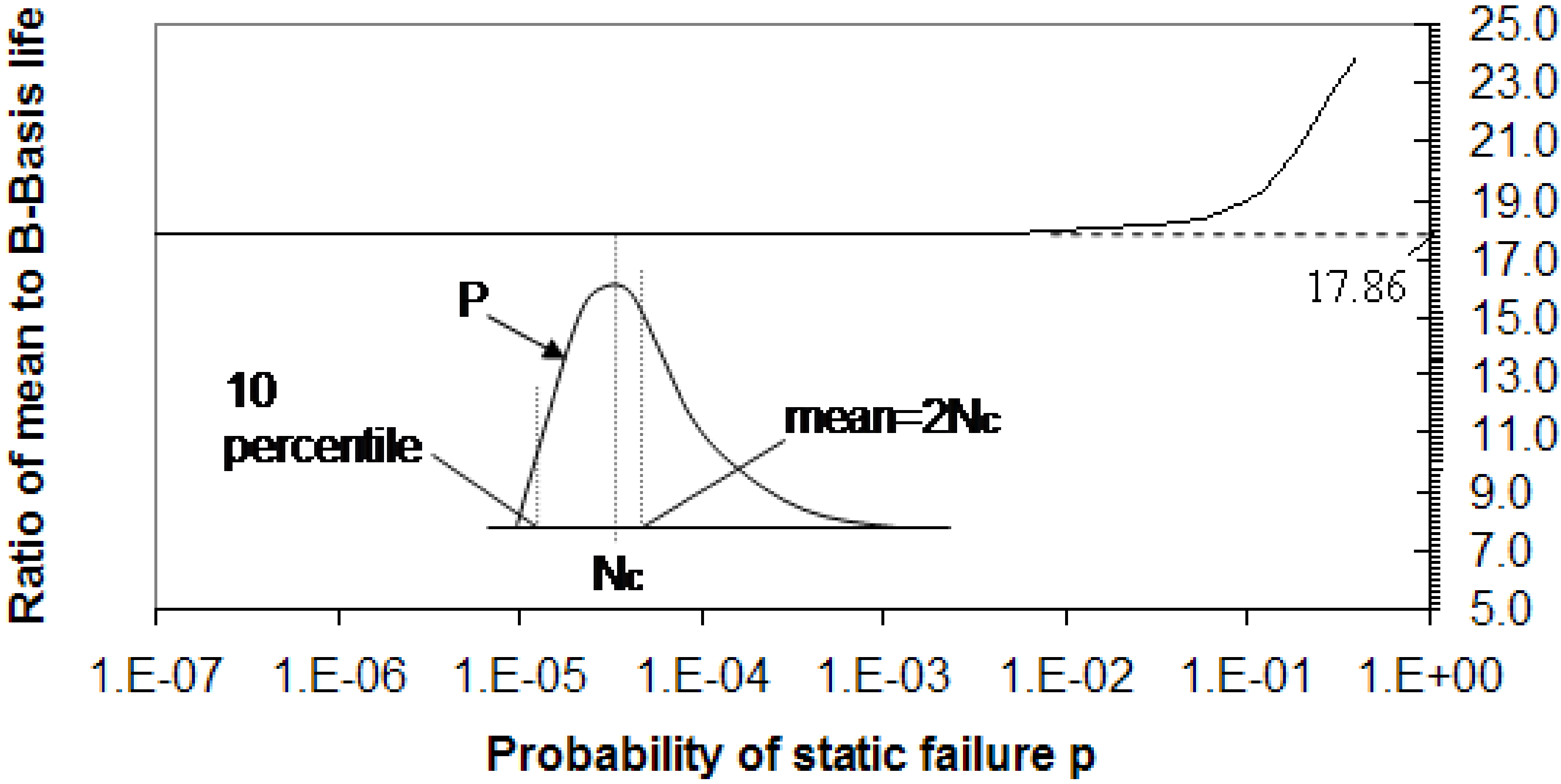
Fatigue predictions for sandwich specimens with BVID



Applications

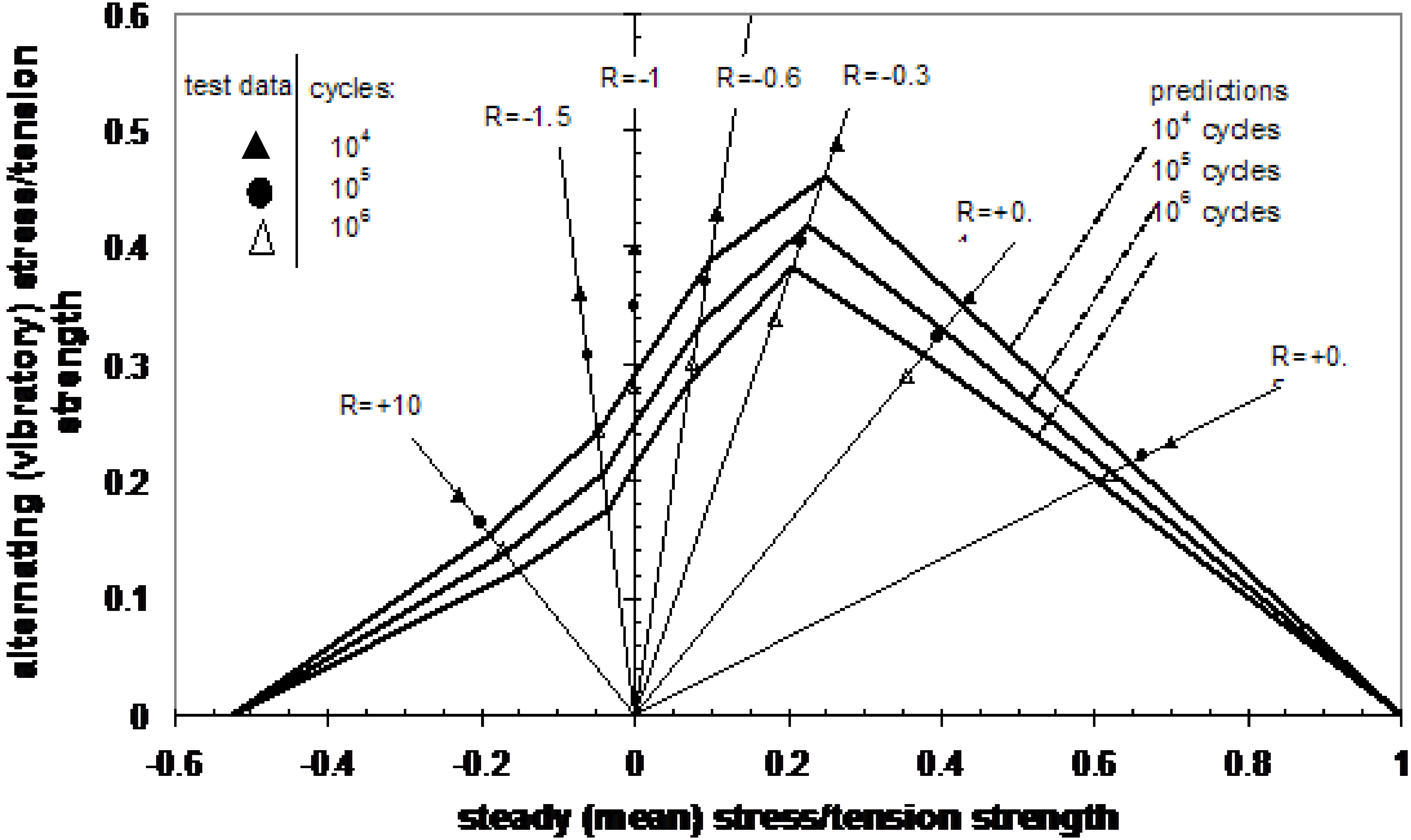
- Fatigue life prediction under constant amplitude
- Determination of B- (or A-) Basis life curve
- “Goodman” diagrams
- Truncation levels for testing
- Extension to spectrum loading

Determination of B-Basis life

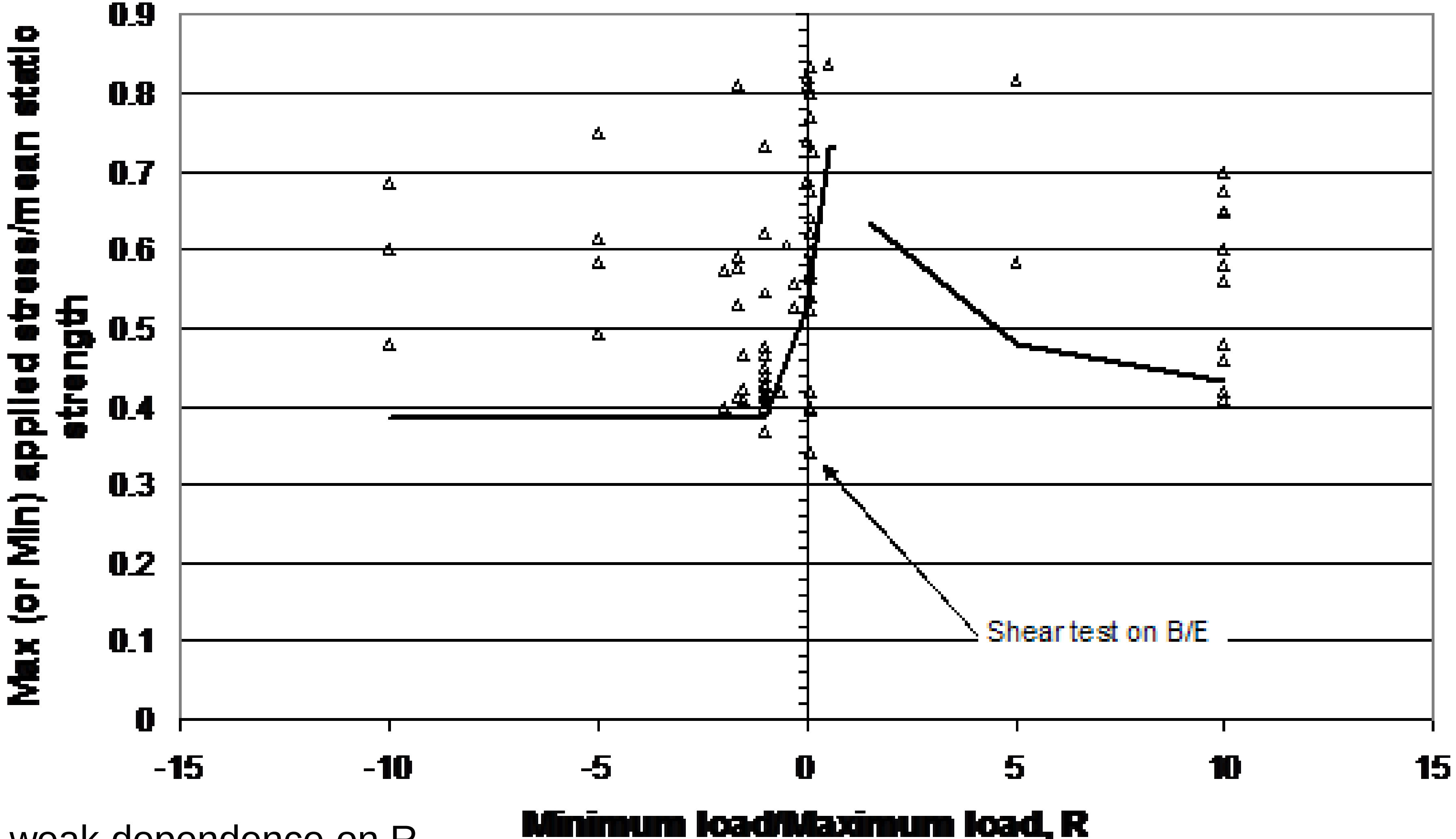


• compare to Northrop report value of 13

“Goodman” diagram



Truncation level determination



- weak dependence on R
- 0.3-0.4 for 1 million cycles

Reminder

- still need to account for environment, material scatter (if not explicitly included in equations)

Conclusions

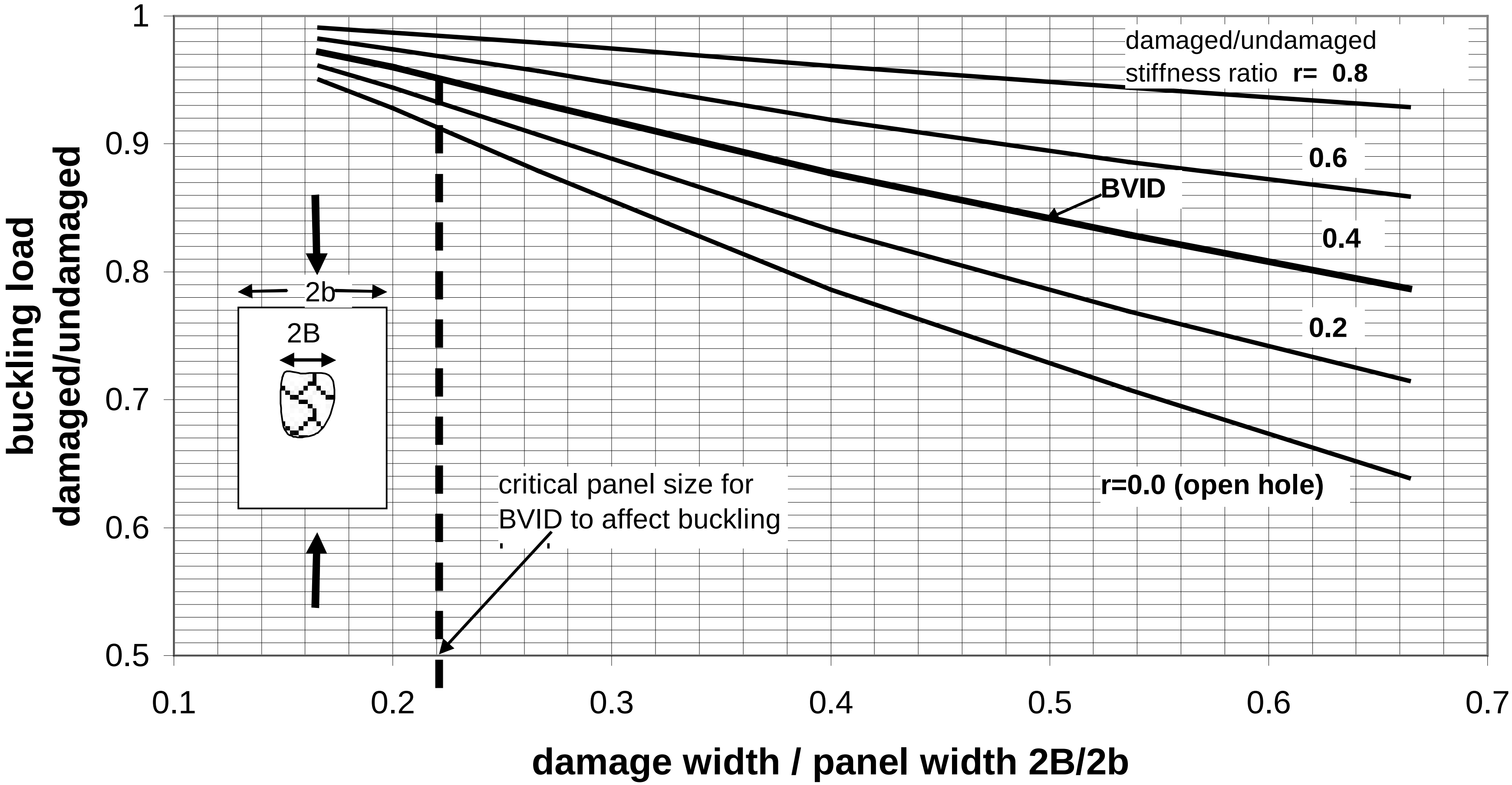
- 0.25” holes and BVID damage for sandwich are equivalent (compression and shear)
- predictions for CAI for sandwich with BVID
- determination of cycles to failure under constant amplitude
- application to:
  - B-Basis life determination
  - Goodman diagrams
  - truncation levels

Caveats

- Hole to Impact equivalence is a function of
  - specimen size
  - maybe material(?)
- Determination of fatigue curves requires further improvements:
  - Non constant value of p (track damage creation and growth)
  - Improved methodology for R-dependence
- “Analysis without testing is almost as bad as testing without analysis”

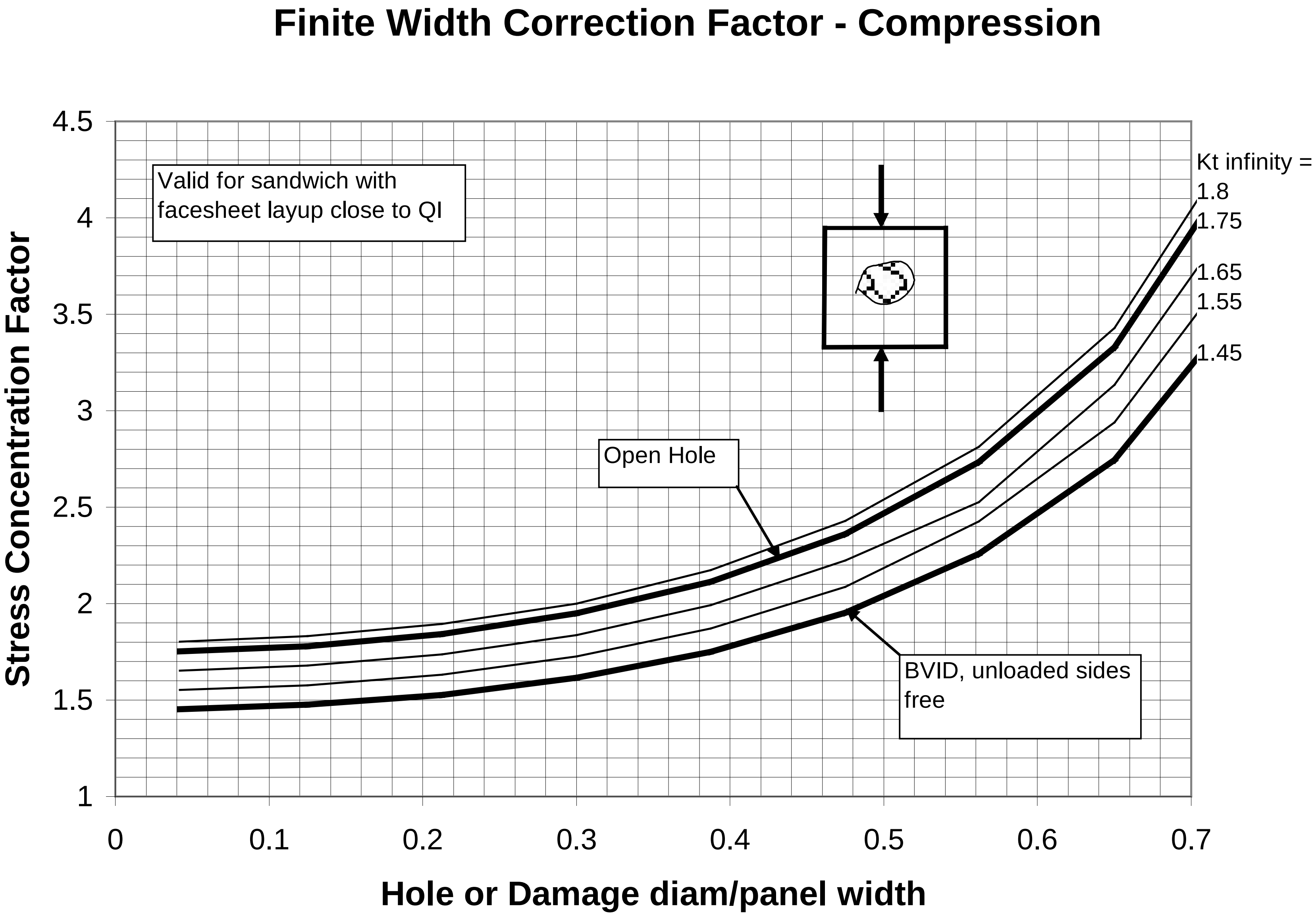
Back-up Slides

Failure mode interaction – notched buckling versus notched strength



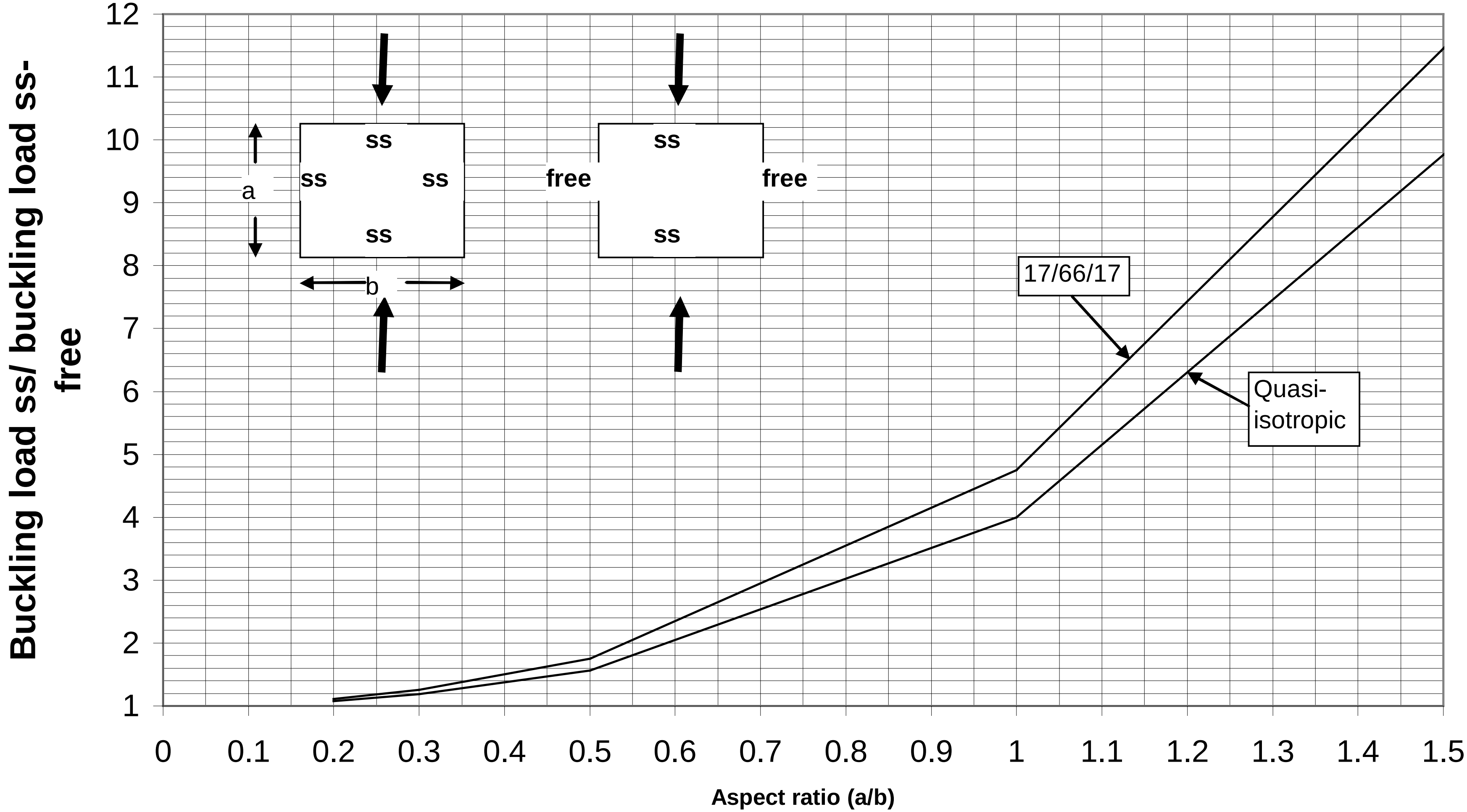
BVID analysis

- Finite width effects
- Boundary condition effects
- BVID as stress concentration
- Predictions vs test results

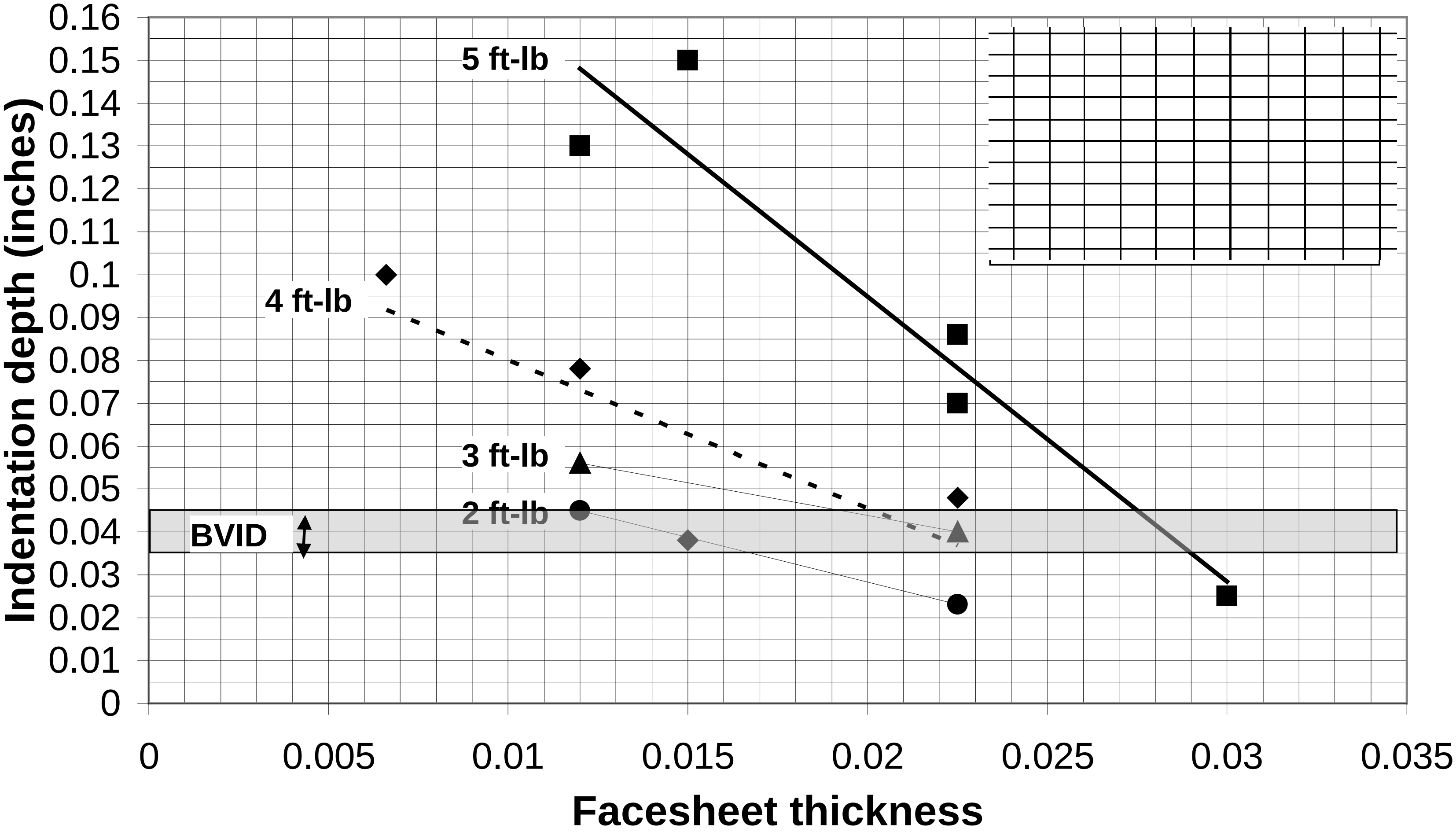


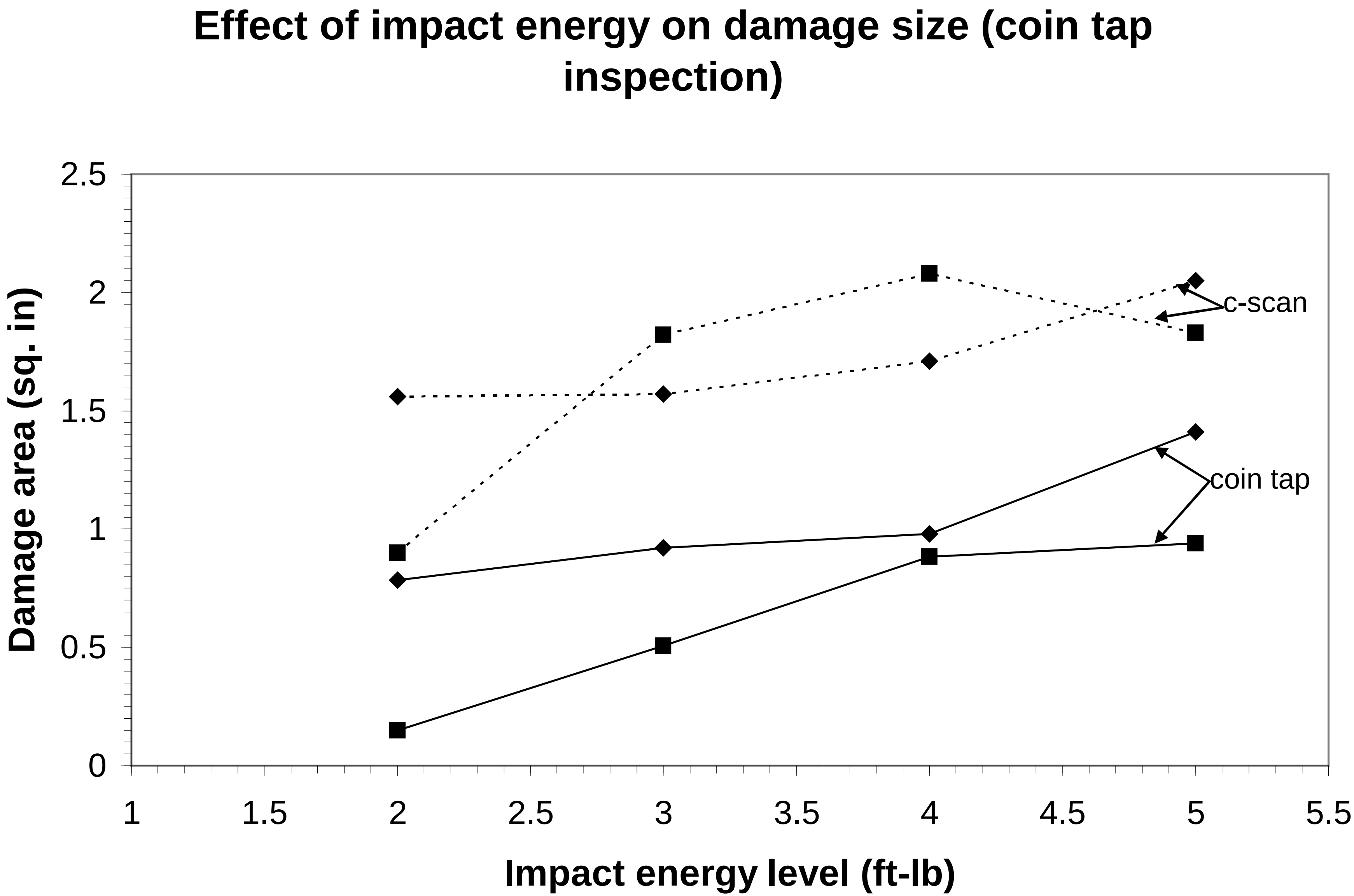
Finite Width Correction Factor - Compression
Stress Concentration Factor
4.5
4
3.5
3
2.5
2
1.5
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Hole or Damage diam/panel width
Valid for sandwich with facesheet layup close to QI
Open Hole
BVID, unloaded sides free
Kt infinity =
1.8
1.75
1.65
1.55
1.45

Relation of buckling loads between all simply supported panel and ss-free panel (sandwich under compression)



Effect of face thickness and energy on indentation depth




Effect of impact energy on damage size (coin tap inspection)
Damage area (sq. in)
Impact energy level (ft-lb)
c-scan
coin tap
0
0.5
1
1.5
2
2.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

References

1. Kassapoglou C., “Compression Strength of Composite Sandwich Structures After Barely Visible Impact Damage”, J. Composites Technology and Research, vol 18, 1996, pp. 274-284.

5. Dost, E.F., Ilcewicz, L.B., and Gosse, J.H., “Sublaminate Stability-Based Modeling of Impact-Damaged Composite Laminates”, Proc. 3d Technical Conf of American Society of Composites, Seattle, Wa, Sep 1988, pp. 354-364.